Transactions IAU, Volume XXXA
Reports on Astronomy 2015-2018
Piero Benvenuti, ed.

DOI: 00.0000/X000000000000000X

COMMISSION 3 **STELLAR EVOLUTION**
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TRIENNIAL REPORT 2015-2017

1. Introduction

Stars are perhaps the must fundamental astronomical objects. They provide the link between large- and small-scale phenomena. The structure and evolution of galaxies depends on stars both through their gravity and their effect in stirring the interstellar medium. Also, their production of dust and enriched gas powers the chemical evolution of galaxies, and provides the raw materials for many subsequent astrophysical processes. Hence the understanding of stars and stellar evolution remains a key ingredient in modern astrophysics. We are currently undergoing a revolution in our understanding of stars, and this report will discuss some of the recent developments.

2. Large Spectroscopic Surveys

The Gaia-ESO Public Spectroscopic Survey has begun at the end of 2011 and was performing high-resolution spectroscopy of some 100 000 Milky Way stars, in the field and in open clusters, down to magnitude 19, systematically covering all the major components of the Milky Way. Apart of the main goal of this survey to provide the first homogeneous overview of the distributions of kinematics and chemical element abundances in the Galaxy, it contributed to stellar evolution studies as well. Casey et al. (2016) revisited the Li-rich giant problem by investigating 20 Li-rich giants discovered by the survey. It was noted that when coupled with models of planet accretion, the observed destruction of hot Jupiters actually predicts the existence of Li-rich giant stars, and suggests that Li-rich stars should be found early on the giant branch and occur more frequently with increasing metallicity. Bouvier et al. (2016) reported the existance of a relationship between lithium content and rotation of young low-mass stars in the 5 Myr old, star forming region NGC 2264. The emergence of a connection between lithium content and rotation rate at such an early age as 5 Myr suggests a complex link between accretion processes, early angular momentum evolution, and possibly planet formation, which likely impacts early stellar evolution and has yet to be fully deciphered. A pilot paper on C and N abundances in stars of three Galactic open clusters observed by the Gaia-ESO survey was published by Tautvaišienė et al. (2015). The observed C and N abundances with those predicted by current stellar evolution models. The C/N ratios of stars in the investigated open clusters Trumpler 20, NGC 4815, and NGC 6705 with turn-off masses from 1.9 to 3.3 $M_{\odot}$ were very close to the predictions of standard first dredge-up models as well as to models of thermohaline extra-mixing (Charbonnel & Lagarde (2010)). They were not decreased as much as predicted by the model by Lagarde et al. (2012) in which the thermohaline- and rotation-induced extra-mixing act together.

The Sloan Digital Sky Survey since 2014 is running its APOGEE-2 spectroscopic survey. The effect of metallicity on the granulation activity was investigated by Corsaro et al. (2017) using APOGEE and *Kepler* data. A higher metallicity increases the amplitude of granulation and meso-granulation signals and slows down their characteristic time scales toward longer periods. The trend in amplitude is in qualitative agreement with predictions from existing 3D hydrodynamical simulations of stellar atmospheres from main sequence to red giant stars. It was confirmed that the granulation activity is not sensitive to changes in the stellar core and that it only depends on the atmospheric parameters of stars. By using *Kepler*'s asteroseismic and APOGEE's spectroscopic data for over 3000 first ascent red giants, Tayar et al. (2017) tested the accuracy of stellar models on the stellar post-main-sequence. When they compared the observational data to theoretical predictions, they found a metallicity dependent temperature offset with a slope of around 100 K per dex in metallicity. Stellar models can be brought into agreement with the data if a metallicity dependent convective mixing length is used, with $\Delta\,\alpha_{\rm ML,YREC} \sim 0.2$ per dex in metallicity, a trend inconsistent with the predictions of three dimensional stellar convection simulations. If this effect is not taken into account, isochrone ages for red giants from the *Gaia* data will be off by as much as a factor of 2 even at modest deviations from solar metallicity ([Fe/H]=0.5).

The unique design of LAMOST Experiment for Galactic Understanding and Exploration (LEGUE) enables it to take 4000 spectra in a single exposure to a limiting magnitude as faint as $R = 19$ at the resolution $R = 1800$. In combination with *Kepler* light-curves, a comprehensive study of flare activity and rotation of 540 M dwarfs, as well as the relationship of the energy release in different layers of stellar atmosphere, was carried out by Yang et al. (2017). It was revealed that the flare activity is related with the rotation and can be described with three phases, and the released energies in different layers of stellar atmosphere with a power law relation. The flare activity and the number fraction of flaring stars in M dwarfs rise steeply near M4, which is consistent with the prediction of a turbulent dynamo. A small enhancement in chromosphere activity may cause a huge rise in flare energy, which suggests that superflares or hyperflares may not need an extra excitation mechanism. A systematic searching of Li-rich metal-poor stars with LAMOST and follow-up observations with Subaru Telescope granted the discovery of 12 very metal-poor stars that have large excesses of Li, including an object having more than 100 times higher Li abundance than the values found in usual objects, which is the the largest excess in metal-poor stars known to date (Li et al. 2018).

The Galactic Archaeology with HERMES (GALAH) survey is a large high-resolution spectroscopic survey using the newly commissioned High Efficiency and Resolution Multi-Element Spectrograph (HERMES) on the Anglo-Australian Telescope (De Silva et al. 2015). The HERMES spectrograph provides high-resolution ($R \sim 28\,000$) spectra in four passbands for 392 stars simultaneously over a 2 deg field of view. This survey will look for fossil remnants of ancient star formation events which have been disrupted and are now dispersed throughout the Galaxy. Chemical tagging seeks to identify such dispersed remnants solely from their common and unique chemical signatures; these groups are unidentifiable from their spatial, photometric or kinematic properties. To carry out chemical tagging, the GALAH survey will acquire spectra for a million stars down to $V \sim 14$ mag and will contribute to stellar evolution studies.

3. Asteroseismology

Significant efforts have been made in the field of asteroseismology also thanks to space missions such as *Kepler.* Indeed the characterization of exoplanets needs the characterization of the host stars and with the second mission of Kepler K2 it has been possible to perform an ensemble asteroseismic analysis on evolved stars with unprecedented accuracy, in particular for what concerns estimates of mass, radius, and age of giant stars (Casagrande et al. 2016; Sharma et al. 2016). Asteroseismology has also been used as a precision tool for exoplanet studies - both for characterizing the host stars of exoplanets (Silva Aguirre et al. 2015) and for calibrating key spectroscopic properties, such as surface gravities of exoplanet hosts in general (Petigura et al. 2017). Asteroseimic ages of dwarfs were also used to test rotation-age relationships in old stars, uncovering surprising departures from the expected decay of rotation in stars less active than the Sun (Angus et al. 2015; van Saders et al. 2016). With large asteroseismic data sets, strong observed correlations between mass and the surface C/N ratio in evolved stars were used to develop mass and age proxies for large spectroscopic surveys (Martig et al. 2016; Ness et al. 2016); this data was also used to test the theory of the first dredge-up.

The first wave of *Kepler.* and CoRoT asteroseismic results demonstrated the potential of asteroseismology for large populations of evolved field stars. Prior to the start of this reporting period, it was demonstrated that virtually all cool giants were high amplitude oscillators and that their frequency patterns could be measured with space data. The complex observed spectra were also discovered to be a consequence of interactions between modes where the restoring force is changes in the potential (g-modes) and ones where the restoring force is changes in pressure (p-modes); in evolved stars their frequencies become comparable, generating mixed modes with diagnostic power about core properties. This led to discoveries included the ability to infer core rotation rates and to distinguish between core-He burning stars and shell H-burning stars on the basis of their observed frequencies.

During the 2015 to 2017 reporting period, these asteroseismic results were extended to a much wider domain in the HR diagram. Tests of core size and rotation were performed for slowly pulsating B stars (Moravveji et al. 2015; Triana et al. 2015), and internal differential rotation was measured for very slowly rotating A stars (Saio et al. 2015). Initial rotational measurements were also obtained for near-MS F stars (Van Reeth et al. 2016). Asteroseismic data was also used to test the theory of stellar structure and evolution, notably in core He-burning stars. The recognized tension between measured and predicted core g-mode spacings was found to have significant implications for He-burning lifetimes and core overshooting (Bossini et al. 2015; Constantino et al. 2015). Finally, a widespread and puzzling phenomenon in the early data - the existence of a population of evolved cool stars with depressed dipole modes - was used to infer the existence of strong core magnetic fields in intermediate mass stars (Fuller et al. 2015).

4. GAIA

Gaia Data Release 1 contains parallaxes for more than 700 Galactic Cepheids and RR Lyræ stars, that have been computed as part of the Tycho-Gaia Astrometric Solution (TGAS). These TGAS parallaxes have been used, along with literature photometry and spectroscopy, to calibrate the zero point of typical period–luminosity and period–Wesenheit relations of classical and type II Cepheids, and the near-infrared period–luminosity, period–luminosity–metallicity and optical luminosity–metallicity relations of RR Lyræ stars. These relations are good starting points towards a recalibration of the extragalactic distance scale that will be possible with unprecedented accuracy when Gaia final data will become available. Asteroseismic data was also used to quantify systematic errors in Gaia parallaxes, which were found to be at the level predicted for DR1.

5. Interferometry of Stellar Surfaces

Significant progress has been made in long-baseline interferometry using optical telescopes over the last decades. Lights of astrophysical sources collected by large apertures with the Very Large Telescope Interferometer (VLTI) or the Keck Interferometer (KI) are combined to provide milli-arcsecond spatial resolution in the near-infrared wavelength domain. VLTI is a very attractive means for scientific research, and several generations of focal instruments have been developed. VINCI is a two-way beam combiner used for commissioning, while AMBER combines three beams of light with low, moderate and high spectral resolution, and is the first-generation general-user near-infrared focal instrument. PIONIER combines four beams of light and is for four-telescope operation. GRAVITY is a multiple-beam-combiner developed recently for two-object imaging. Stellar surfaces have been successfully imaged with AMBER and PIONIER, while first light has been reported for GRAVITY.

Ohnaka et al. (2017) observed Antares, which is a well studied red supergiant close to Earth, with the near-infrared VLTI instrument AMBER, and reconstructed its images. The images are the best ever of a star's surface and atmosphere, and furthermore, the images are velocity-resolved, providing us with a three-dimensional picture of the dynamics of stellar atmospheres from deep layers to the outer atmosphere. The result shows vigorous upwelling and downdrafting motions of several huge gas clumps at velocities ranging from about -20 to $+20$ km s^{-1} in the atmosphere, which extends out to 1.7 stellar radii. The reconstructed images are very helpful for us to identify the process of the turbulent atmospheric motions.

Paladini et al. (2018) observed the giant star π^1 Gruis with the four-telescope beam combiner PIONIER mounted at the VLTI. Images of the stellar surface are reconstructed from the interferometric data and the surface is shown to have a complex convective pattern with an average intensity contrast of 12 per cent. The large granulation cells on the surface have a typical size of about 1.2×10^{11} metres, corresponding to 27 per cent of the diameter of the star. Their measurements agree well with the scaling relations between granule size, effective temperature and surface gravity that are predicted by simulations of stellar surface convection.

Complementary to resolved stellar surface observation in the near infrared as discussed above, millimetre and sub-millimetre interferometry with ALMA is also about to reach comparable spatial scales. By studying the inhomogenous atmosphere of Betelgeuse at the 338 GHz continuum O'Gorman et al. (2017) demonstrated the great potential of ALMA in this field. With the to be expected information on velocity fields as well as polarimetric properties a fantastic diagnostic tool is about to materialize in the near future.

6. Advances in the theory of supernova explosions

The last three years have seen considerable advances in core-collapse supernova models with the advent of the successful first three-dimensional (3D) simulations of neutrino-driven explosions including multi-group, three-flavour transport (e.g. Melson et al. 2015; Lentz et al. 2015) for progenitors between $9.6M_\odot$ and $20M_\odot$. This is partly due simply to the growing number of rigorous 3D simulations by several groups. In addition, some new key ingredients for robust explosions have been identified and added to simulations. This includes hitherto neglected microphysics such as muonisation (Bollig et al. 2017), and pre-collapse seed perturbations from convective burning (Couch et al. 2012; Müller et al. 2016). Moreover, long-time simulations over several seconds in two (Bruenn et al. 2016) and three dimensions (Müller et al. 2017) have become feasible and are starting to reach plausible explosion energies and neutron star masses, kicks, and spins, although they cannot yet explain the full range of observed explosion parameters.

Progress has also been made on connecting multi-dimensional core-collapse supernova models to observations, albeit using less rigorous, parameterised simulations (e.g. Utrobin, Janka & Müller 2015; Wongwathanarat et al. 2017). These recent efforts strongly suggest that neutrino-driven explosions can naturally explain the peculiar phenomenology of ejecta mixing and nucleosynthesis in well-studied cases like SN 1987A and Cas A.

Work on magnetorotational models for hyperenergetic supernovae has continued in recent years as well. While the disruption of MHD-driven jets by the kink instability remains a potential problem in 3D models, progress has been made towards a better understanding of relevant field amplification processes like the magnetorotational instability (MRI) by means of local (Rembiasz et al. 2016) and short global simulation with ultra-high resolution (Mösta et al. 2015). In particular, the importance of non-ideal effects on the growth of the MRI in proto-neutron star has been recognised and investigated (Guilet, Janka, & Müller 2015).

7. Multi-dimensional Hydrodynamical Modelling for Stars

Massively parallel computing facilities are now enabling numerical simulations of hydrodynamics in stellar interiors. Recent investigations have looked at the complex phenomenon of "convective-reactive" phenomena, where the timescale for mixing of fuel is comparable to the timescale for burning the fuel (Woodward, Herwig and Lin 2015; Ritter et al 2018). This may be related to the development of i-process nucleosynthesis (Clarkson et al. 2018), being intermediate between r- and s-process neutron capture, and a promising way to explain the CEMP-r/s stars (Hampel et al. 2016).

We are also making serious advances in our understanding of convection through similar calculations (Jones et al. 2017; Cristini et al. 2017; Arnett & Meakin 2016; Arnett et al. 2015). Indeed combining such work with asteroseismology can provide interesting results on the abundance profile at convective borders, as shown by Arnett & Moravveji (2017).

Three-dimensional radiation hydrodynamical codes (e.g. CO^{5}BOLD, Freytag et al. 2013, and the STAGGER grid, Collet et al. 2011; Magic et al. 2015) are increasingly being used to determine abundances from better models of line-forming regions. Grids of atmospheric models dedicated to specific parts of the HR diagram are now available (e.g. for white dwarfs see Tremblay et al. 2015), and 3D atmospheres are being used to investigate not only the effect of higher dimensions but also LTE vs non-LTE effects within these higher dimensions. Some of the inferred differences can be substantial. For example, Nordlander et al. (2017) analysed the most metal-poor star known, SMSS0313-6708. and found that 3D NLTE models resulted in increases of 0.5 dex in Mg, Al and Ca and as much as 0.8

dex for Fe. Significant corrections have been found for less metal-poor stars, especially for O (Collet et al. 2018). Other examples of recent work include studies of O (Prakapavicius et al. 2017), Mg (Bergemann et al. 2017; Thygesen et al. 2017). The future clearly lies in such calculations, not only for their spectroscopic applications but also for their input to 1D stellar models (e.g. Salaris & Cassisi 2015; Magic, Weiss & Asplund 2015). We also note the development of MUSIC, a multi-dimensional implicit hydrodynamics code (Goffrey et al. 2017).

8. Modelling of Massive Stars and LIGO

Massive stars, by which we mean those stars evolving through all the stable nuclear burning stages and eventually exploding as core collapse supernovæ, play a fundamental role in the evolution of the Universe. In particular, a good knowledge of their evolution is required in order to shed light on many topical subjects like the chemical evolution of the Universe, the UV outputs of the first stars, the properties of the Galactic and the Magellanic Clouds Wolf–Rayet stars, the origin of the Extremely Metal Poor stars, the final fate of massive stars and how they explode as core collapse supernovae of different types, the nature of the progenitors of the long Gamma Ray Bursts, the rotation rate of young pulsars and black holes that are produced after the explosion and so on.

In the last three years great theoretical efforts have been made in order to refine as much as possible the massive star models as well as to include additional physical processes like, e.g., stellar rotation and magnetic fields. In spite of these efforts, however, the presupernova evolution is still largely affected by the well known, long standing, uncertainties of the stellar evolution, i.e., the mass loss and all the physical phenomena that require a multi-dimensional treatment like, e.g., convection and rotation. In this context, a great effort has been made by a number of groups in order to include the most recent and reliable prescriptions for the mass loss during all the various evolutionary phases (and also the most updated input physics) (Frischknecht et al. (2016); Meynet et al. (2013); Georgy et al. (2013, 2012); Ekström et al. (2012); Potter et al. (2012); Chieffi & Limongi (2013)). Unfortunately the situation is not well established yet since, from one side, there is no mass loss recipe that can be definitively preferred to all the others, from another side the adoption of the various mass loss prescriptions available in literature (Vink et al. (2001); de Jager et al. (1988); Nugis & Lamers (2000); Gräfener & Hamann (2008); van Loon et al. (2005)) provide very different evolutionary results – but progress continues to be made in measuring mass-loss rates as a function of stellar parameters, both for low-mass cool giants (McDonald & Zijlstra (2015, 2016)) and more massive cool giants and supergiants (Goldman et al. (2017); Beasor & Davies (2016, 2018); Javadi et al. (2018)). In addition to that, most of the massive stars evolve during the so called Luminous Blue Variable (LBV) phase, where they experience strong episodes of dynamical mass ejection. Given the transient nature of this phenomenon, as well as its sporadic occurrence, a continuous monitoring of the sky would certainly greatly push forward our understanding of this mysterious phase. In this context, we expect that the multiband high performance monitoring capabilities of LSST will allow us to significantly increase the number of confirmed LBV stars. In this way we will have more accurate determinations of the length of the LBV phase, the properties (mainly the location in the HR diagram) of the stars during this unstable stages and the total amount of mass lost, either in total and per eruption. These data will greatly improve our understanding of this phase as well as its impact on the evolution of massive stars.

The effect of rotation on the evolution and nucleosynthesis of massive stars has been also greatly investigated in these last years by a number of groups (Frischknecht et al.

(2016); Meynet et al. (2013); Georgy et al. (2013, 2012); Ekström et al. (2012); Potter et al. (2012); Chieffi & Limongi (2013)). Let us recall that the effects of rotation on massive star evolution can be classified in four categories: 1) axial rotation deforms the star and therefore has an impact on the hydrostatic configuration; 2) axial rotation triggers many instabilities in the stellar interior driving the transport of the angular momentum and of the chemical species; 3) axial rotation has an impact on the way stars are losing mass through radiative winds and through mechanical mass losses; 4) rotation may in some circumstances activate dynamo mechanisms and thus have an impact on the magnetic field which in its turn has an impact on the rotation of stars. Through all these different effects, rotation may change, even significantly, the main evolutionary properties of a massive star, i.e., lifetimes, core masses, nucleosynthesis, presupernova structure, and so on. Despite the great efforts devoted to these studies, the results obtained differ significantly among the various groups and therefore cannot be considered well established. In this context, one example is connected to the effects of the rotation induced mixing which is one of the most important consequences of rotation. Present massive star models show that all other parameters being kept fixed (initial mass, initial rotation), rotation driven mixing is more efficient at low metallicity. This more efficient mixing allows diffusion of elements between the He-burning core and the H-burning shell at very low metallicity. This boosts the production of some isotopes like ^{13}C, ^{14}N, ^{22}Ne and the *s*-process elements (Frischknecht et al. (2016)) and may have an impact on the early phases of the chemical evolution of galaxies (Cescutti & Chiappini (2010); Chiappini et al. (2011)), in particular, among the other things, may account for the high N abundance observed in low metallicity low mass halo stars (Chiappini et al. (2006)). Although there is a common agreement on this general behaviour, the results obtained by the various groups differ quantitatively, even substantially. The reason for this is due to the great uncertainties connected to the inclusion of rotation, i.e. a typical multi-dimensional phenomenon, in a 1D stellar evolution code. In particular, a key question is the efficiency of the rotation induced mixing that, because of all the assumptions that one is forced to do to treat rotation in one dimension, must be necessarily calibrated. Different authors adopted different techniques to perform such a calibration, i.e. Heger et al. (2000) and Chieffi & Limongi (2013) require a surface enrichment of nitrogen of the order of 2–3 in solar metallicity models with initial mass in the range 10–20 $M_\odot$, while Brott et al. (2011) try to reproduce the observed nitrogen abundance as a function of the projected rotation velocity in the LMC samples of the FLAMES survey (Hunter et al. (2009)). These different approaches together to different schemes (diffusion/advection) adopted to treat the rotation driven mixing provide substantially different results.

After the explosion, massive stars leave compact remnants, i.e. neutron stars or black holes, that can be identified through several observational evidences. In this context, massive stars became recently very interesting in the framework of the multi-messenger astronomy. The direct detections of gravitational waves, GW150914, GW151226, GW170104, GW170608, GW170814 (Abbott et al. (2016a,b,c,d, 2017a,c,d)) have been associated with the merger of two black holes, presumably of stellar origin, GW150914 and GW170608 being associated to the largest ($\sim$ 29–36 $M_\odot$) and smallest ($\sim$ 7–12 $M_\odot$) progenitor masses, respectively. GW170817, on the contrary, was the first gravitational wave detection presumably due to the merging of two neutron stars (Abbott et al. (2017b)). Which is the evolutionary path of a massive star leading to the formation of a black hole or a neutron star? How this evolutionary path and the mass of the remnant depend on the initial stellar parameters, i.e. mass, metallicity, rotation velocity? Which is the expected frequency of BH–BH, BH–NS and NS–NS binaries and with which mass ratio? The answers to all these questions are needed for a key step forward for a better knowledge of the gravitational wave sources, for a correct interpretation of the next detections we expect from the ground based instruments (Advanced-LIGO, Advanced-VIRGO) as well as from the next generation of space detectors that will be fully operating in the coming 30 years (eLISA). In general the remnant mass of a core collapse supernova depends not only on the presupernova evolution but also on the dynamics of the explosion.

At present there is no self consistent, well established model for the core collapse supernovæ that is able to obtain the explosion with the typical observed properties, even with the most updated hydrodynamical models and microphysics ingredients. Work is underway by all the theoretical groups to better understand the problem and we may expect progresses in the next future (see above in this document). For all these reasons, in the last years there has been an increasing interest in determining whether a star with a given mass blows up or collapses to a black hole simply looking at one or two parameters of the one-dimensional models from stellar evolution calculations (O'Connor & Ott (2011, 2013); Ugliano et al. (2012); Sukhbold & Woosley (2014); Pejcha & Thompson (2015); Ertl et al. (2016); Sukhbold et al. (2016)). In these studies the remnant after the explosion is computed by means of more or less sophisticated (still) artificially induced explosions and it has been shown the existence of "islands of explodability" resulting from the non monotonicity of the properties of the stars at the presupernova stage as a function of the initial mass. This result, however, has not been confirmed by other groups working in this field and it may critically depends on the details of the presupernova evolution (e.g., mass loss during the various stages, especially during the Wolf–Rayet phase), as well as on the details of the artificially induced explosion (e.g., neutrino treatment, nuclear equation of state, and so on). For all these reasons this result cannot be considered well established yet and needs to be investigated in more detail also by other groups.

9. Closing remarks

The development of large spectroscopic and time-variability surveys and the realisation of the potential of asteroseismology are perhaps the main drivers of stellar evolution studies at present, but interferometric imaging and infrared capabilities to study mass loss, too, continue to advance. When combined with significant improvements in multi-dimensional hydrodynamical studies, we may finally be reaching a time when we can remove some of the traditional roadblocks to improved quantitative understanding of stars. We expect the next tri-ennium to continue in producing significant advances.

John Lattanzio
President of the Commission, with input from all OC members
and Dr Bernhard Müller

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